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Design and Comparison of a Novel Controller Based on Control Lyapunov Function and a New Sliding Mode Controller for Robust Power Flow Control Using UPFC

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ABSTRACT

Unified power flow controller (UPFC) is a complex Flexible AC Transmission System (FACTS) device. UPFC is capable of controlling selectively the transmission line parameters in order to power flow control and power oscillation damping. This paper presents an advance to power flow control in a power system with UPFC by two nonlinear controllers; one based on the Control Lyapunov Function (CLF) (named also as Direct Lyapunov Method (DLM)) and the other is based on Sliding Mode Control. A state variable control scheme is implemented to challenge the problems of reference tracking, robustness against parameter uncertainty and rejecting external disturbances. Chattering phenomena and discontinuity of the controllers are also removed to obtain a continuous and smooth controller. The proposed controllers are robust against uncertainties and reject external disturbances. Simulation results are given to illustrate the effectiveness and robustness of the proposed algorithm. As the most simply measurable states of the system are used in suggested controllers, there is no need to design state space variable observer system.

Key words:FACTS, UPFC, Power Flow Control, Lyapunov Stability, Control Lyapunov Function, Sliding Mode Control

1. INTRODUCTION

Deregulated environments utilized with FACTS devices reduce investment costs, improve system security, and enhance system reliability and power quality [1,2]. FACTS devices control the transmission line parameters to achieve a better system performance. FACTS devices and their applications are covered in full by [1].

Among FACTS devices, the Unified Power Flow Controller (UPFC) provides a suitable control for impedance, phase angle, active and reactive power of a transmission line [3].

UPFC's capabilities have been investigated in different areas such as; power flow control [2, 4, 5], voltage control [6], transient stability improvement [7], oscillation damping [8-10]. In addition, UPFC has been discussed in vast variety of control system investigations[5] such as:

Neural network based controller [10], fuzzy neural network approach [11], fuzzy control [12], controllers based on the optimization algorithms [13, 14], are some of the intelligent controllers presented in papers.

Nonlinear finite-time Lyapunov theory based controller

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[5], feed-back linearization [15-17], a nonlinear control method based on A. Isidori [18], back-stepping design [19], optimal control [20], structured singular value (μ-synthesis) [21] and H_2 approach [22] are some nonlinear approaches have been discussed in literatures. Besides in the field of Sliding Mode Control (SMC) techniques, some researches are implemented on Electric Power System such as SMC of excitation system [23], Decentralised SMC of PSS [24], Adaptive Neuro SMC of SVC [25], Decentralized Sliding Mode Block Control of PSS and AVR of multi-machine power systems [26] Lyapunov-Based Decentralized Excitation and Voltage Control [27], which are not applied to UPFC, and Super Twisting SMC of UPFC [28].

Generally, linearised systems are valid only for a given operating point. The fundamental issue with standard linear or optimal controller is in using a linearised system model and thus raising the question of robustness. The controller may be ineffective when system operating point or parameters change [5] whilst power systems exhibit nonlinear behavior [29]. Generally, Intelligent controllers have the problem of iteration based results [5].

Some above-mentioned control techniques have insufficient proficiency in the presence of large disturbances. Nonlinear control strategies have confirmed better robustness and disturbance rejection properties [5].

Unfortunately, nonlinear controllers discussed among published papers have high order complexities or inquires global system state sensing, and some have exhausting design procedures.

In line with above discussion, this paper addresses the problem of nonlinear controller design based on Control Lyapunov Function (CLF) and Sliding Mode Control (SMC) for power flow control in a power system transmission line. Both controllers; CLF-based and SMC track the references precisely within a little settling time and are robust against parameter uncertainty and external disturbances.

The CLF nonlinear controller design method has not been applied to power flow control of transmission line with UPFC in the open literature. For the sake of brevity, the design procedure of CLF [31] and SMC method [32] are not discussed in this paper, and only the mathematical approaches and the stability approves of the proposed controllers are included. Besides, the designed controllers, CLF-based and SMC, in this paper are not used in the open literature in order to control the UPFC until now.

1.1. Notations

Through the paper, $(.)^T$ represents the transposition operator, and | . | is the absolute value. Subscripts 'd' and 'q' represent the direct and quadrature axes components, respectively (i.e. $x = x_d + jx_q$).

The later sections of this paper are as follows: The suitable model of the UPFC for power flow control studies is described in Section 2. In Section 3, CLF and SMC are designed and the stability of the proposed controller is mathematically approved and validated. The simulation results are presented in Section 4. Finally Section 5 provides some concluding remarks.

2. MATHEMATICAL MODEL OF UPFC

FACTS devices, including STATicCOMpensator (STATCOM), Unified Power Flow Controller (UPFC), Interline Power Flow Controller (IPFC), Multi-Terminal UPFC (M-UPFC) and the Center Node UPFC (C-UPFC) are all based on Voltage-Source Converter (VSC) modules [5, 18].

UPFC consists of two back to back voltage source converters connected through a common dc link [4].

Fig. 1 demonstrates the single phase and steady state [5] representation of UPFC installed in a power system, which consists of an excitation transformer, a boosting transformer, two three-phase voltage source converters (VSCs) and a DC link capacitor. Note that the subsequent calculations are based on the diagram where shunt converter is connected to the bus named "V_s".

The current equations of the system can be expressed by [5]:

$$\begin{aligned} \frac{di_{sep}}{dt} &= \left(-R_{se}i_{sep}+v_{sep}+v_{sp}-v_{rp}\right)/L_{se} \\ \frac{di_{shp}}{dt} &= \left(-R_{sh}i_{shp}+v_{shp}-v_{sp}\right)/L_{sh} \end{aligned} \tag{1}$$

where, $p = a,b,c$ is any phase of the three phase system and $R_{se} = R_{line} + R_{se,trans}$, $L_{se} = L_{line} + L_{se,trans}$ are resistance and inductance of the transmission line plus the resistance and leakage inductance of the series transformer. The i_{se} is the current through the transmission line. R_{sh}, L_{sh} and i_{sh} are resistance, inductance and current of the shunt converter, respectively. v_{se} and v_{sh} are injected series and shunt voltage, v_s, v_r are voltage of the sending and receiving ends, respectively.

Using Park's transformation [33], (1) can be transformed into a "d, q" reference frame as (2):

$$\frac{d}{dt}\begin{bmatrix} i_{sed} \\ i_{seq} \end{bmatrix} = \frac{1}{L_{se}}\left(\begin{bmatrix} -R_{se} & L_{se}\omega \\ -L_{se}\omega & -R_{se} \end{bmatrix}\begin{bmatrix} i_{sed} \\ i_{seq} \end{bmatrix} + \begin{bmatrix} v_{sed}+v_{sd}-v_{rd} \\ v_{seq}+v_{sq}-v_{rq} \end{bmatrix}\right)$$
$$\frac{d}{dt}\begin{bmatrix} i_{shd} \\ i_{shq} \end{bmatrix} = \frac{1}{L_{sh}}\left(\begin{bmatrix} -R_{sh} & L_{sh}\omega \\ -L_{sh}\omega & -R_{sh} \end{bmatrix}\begin{bmatrix} i_{shd} \\ i_{shq} \end{bmatrix} + \begin{bmatrix} v_{shd}-v_{sd} \\ v_{shq}-v_{sq} \end{bmatrix}\right) \quad (2)$$

where $\omega = 2\pi \times freq$, where $freq$ is the fundamental frequency of the supply voltage.

Assume that the d-axis lies on the space vector of the sending end voltage 'v_s'. Thus $v_s = v_{sd} + jv_{sq} = v_{sd} + j0$ [2, 5].

Equation (2) can be rewritten in the form of state space.

$$\dot{x} = Ax + Bu + Non + d$$
$$y = Cx \quad (3)$$

where, $x = \begin{bmatrix} i_{sed} & i_{seq} & i_{shd} & i_{shq} \end{bmatrix}^T$, y, Non, d and $u = \begin{bmatrix} v_{sed} & v_{seq} & v_{shd} & v_{shq} \end{bmatrix}^T$ are state vector, output vector, vector of nonlinear terms, disturbance and uncertainty vector, and input vector, respectively. Assuming $y = x$, results in C to be the unity matrix.

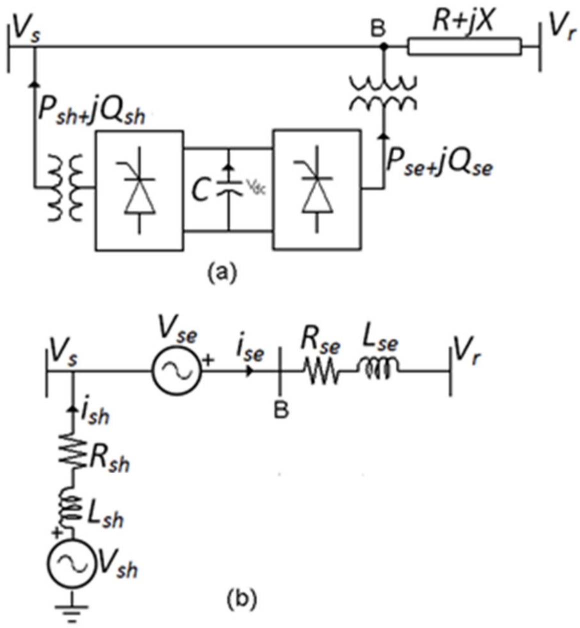

Fig. 1. (a) Schematic diagram of the UPFC system. (b) Single phase representation of a power system with UPFC.

Neglecting the losses in the converters [4, 5]:

$$P_{dc} = P_{se} + P_{sh} \quad (4)$$

where P_{se} , P_{sh} and P_{dc} are active powers of the series and shunt converters and DC link power, respectively and are formulated as follows [5]:

$$P_{se} = \frac{3}{2}\left(v_{sed}i_{sed} + v_{seq}i_{seq}\right) \quad (5)$$

$$P_{sh} = \frac{3}{2}\left(v_{shd}i_{shd} + v_{shq}i_{shq}\right) \quad (6)$$

2.1. DC Link Model

The current and active power of the DC link is expressed in (7) and (8), respectively [4, 5].

$$i_{dc} = -C\frac{dv_{dc}}{dt} \quad (7)$$

$$P_{dc} = v_{dc} i_{dc} = v_{dc}\left(-C\frac{dv_{dc}}{dt}\right) = -Cv_{dc}\dot{v}_{dc} = -\frac{1}{2}C\frac{d v_{dc}^2}{dt} \tag{8}$$

where, C, v_{dc}, i_{dc} are capacitance, voltage and current of the DC link, respectively.

By substituting (4) into (8) we have [4, 5]:

$$\frac{dv^2{}_{dc}}{dt} = -\frac{2}{C}\left(P_{se} + P_{sh}\right) \tag{9}$$

2.2. Design of the Suggested Nonlinear Controllers

In this section two novel controllers are proposed based on CLF and SMC. Stabilization of the proposed controllers is mathematically approved by the second method of Lyapunov stability theorem.

2.2.1. System description, problem formulation and preliminaries

System description, stabilization problem formulation, and some necessary lemmas are presented by the following.

Lemma 1. Lyapunov's second method for stability[27, 34]

Consider a system in the form of

$$\dot{x} = f(x), f(0) = 0, x \in \Re^n \tag{10}$$

where $f : D \to \Re^n$ is continuous with respect to "*x*" on an open neighborhood "*D*" of the origin *x=0*. Assume that there exists a continuous differential positive-definite function $V(x) : \Re^n \to \Re$, such that: $\dot{V}(x) \le 0, \forall x \in D$ then the system is asymptotically stable in the sense of Lyapunov.

2.2.2. Power system equation used in controller design procedure

In order to apply the controller design techniques, error dynamics of the system is calculated.

$$e = x^* - x$$
$$\dot{e} = \dot{x}^* - \dot{x} \tag{11}$$

where x^* is the vector of reference signals.

With known desired active and reactive power flow through transmission line and shunt converter, the reference currents of series and shunt converters are obtained as follows [5]:

$$i^*{}_{sed} = \frac{2}{3}\frac{P^*{}_r v_{rd} + Q^*{}_r v_{rq}}{v^2{}_{rd} + v^2{}_{rq}},\ i^*{}_{seq} = \frac{2}{3}\frac{P^*{}_r v_{rq} - Q^*{}_r v_{rd}}{v^2{}_{rd} + v^2{}_{rq}}$$
$$i^*{}_{shd} = \frac{2}{3}\frac{P^*{}_{sh} v_{sd} + Q^*{}_{sh} v_{sq}}{v^2{}_{sd} + v^2{}_{sq}},\ i^*{}_{shq} = \frac{2}{3}\frac{P^*{}_{sh} v_{sq} - Q^*{}_{sh} v_{sd}}{v^2{}_{sd} + v^2{}_{sq}} \tag{12}$$

The control block diagram of shunt and series converters is shown in Fig. 2.

From (3) and (11) it could be pointed out that:

$$\dot{e} = Ae + \dot{x}^* - Ax_d - Non - Bu - d$$
$$\dot{e} = [F_i - b_i u_i - d] \tag{13}$$

where $F = [F_i]$ is a nonlinear function of the system states, b_i are the coefficients of the input vector, u is the input vector. With no loss of generality, it can be presumed that $\dot{x}^* = 0$ [5].

From (2) and (13) we have:

$$\begin{cases} \dot{e}_1 = -k_1 e_1 - \omega x_2 + k_1 x_1^* - k_2 (u_1 + v_{sd} - v_{rd}) - d_1 \\ \dot{e}_2 = -k_1 e_2 + \omega x_1 + k_1 x_2^* - k_2 (u_2 - v_{rq}) - d_2 \\ \dot{e}_3 = -k_3 e_3 - \omega x_4 + k_3 x_3^* - k_4 (u_3 - v_{sd}) - d_3 \\ \dot{e}_4 = -k_3 e_4 + \omega x_3 + k_3 x_4^* - k_4 (u_4) - d_4 \end{cases} \tag{14}$$

where $k_1 = \frac{R_{se}}{L_{se}}, k_2 = \frac{1}{L_{se}}, k_3 = \frac{R_{sh}}{L_{sh}}, k_4 = \frac{1}{L_{sh}}$, $d = [d_1, d_2, d_3, d_4]^T$

$$B = \begin{bmatrix} b_1 & 0 & 0 & 0 \\ 0 & b_2 & 0 & 0 \\ 0 & 0 & b_3 & 0 \\ 0 & 0 & 0 & b_4 \end{bmatrix} = \begin{bmatrix} k_2 & 0 & 0 & 0 \\ 0 & k_2 & 0 & 0 \\ 0 & 0 & k_4 & 0 \\ 0 & 0 & 0 & k_4 \end{bmatrix}$$

2.2.3. Control Lyapunov Function Based Nonlinear Controller design

To stabilize the error system (14) a nonlinear control law is suggested as follows:

Proposed controller based on CLF

The system (14) with the control law of (15) is stable and its trajectories converge to the equilibrium *e(t)=0*

$$\begin{cases} u_1 = (\omega |x_2| + k_1 |x_1^*| + k_2 |v_{sd} - v_{rd}| + g_1 + d_m) S_1 / k_2 \\ u_2 = (\omega |x_1| + k_1 |x_2^*| + k_2 |v_{rq}| + g_2 + d_m) S_2 / k_2 \\ u_3 = (\omega |x_4| + k_3 |x_3^*| + k_4 |v_{sd}| + g_3 + d_m) S_3 / k_4 \\ u_4 = (\omega |x_3| + k_3 |x_4^*| + g_4 + d_m) S_4 / k_4 \end{cases} \tag{15}$$

where, $S_i = sign(e_i), i = 1,2,3,4$, is the sign function, $g_i, i = 1,\ldots,4$ and d_m are constants to tackle the uncertainties and disturbances, respectively.

Proof. Consider the following positive definite function as a candidate for the Lyapunov function.

$$V(t) = \sum_{i=1}^{4} |e_i| \tag{16}$$

Its derivative with respect to time is

$$\dot{V}(t) = \sum_{i=1}^{4} \dot{e}_i \, sgn(e_i) \tag{17}$$

Replacing $\dot{e}_i$ from (14) into (17) and considering $e_i \, sgn(e_i) = |e_i|$, yields:

$$\begin{aligned} \dot{V} = & -k_1 |e_1| + S_1(\omega e_2 + k_1 x_1^* - \omega x_2^* - k_2(v_{sd} - v_{rd}) - d_1) - k_2 S_1 u_1 \\ & -k_1 |e_2| + S_2(-\omega e_1 + k_1 x_2^* + \omega x_1^* + k_2 v_{rq} - d_2) - k_2 S_2 u_2 \\ & -k_3 |e_3| + S_3(\omega e_4 + k_3 x_3^* - \omega x_4^* + k_4 v_{sd} - d_3) - k_4 S_3 u_3 \\ & -k_3 |e_4| + S_4(-\omega e_3 + k_3 x_4^* + \omega x_3^* - d_4) - k_4 S_4 u_4 \end{aligned} \tag{18}$$

From the fact that $-k|e| \le 0$, and $-d_i - d_m \le 0$ where $d_m = max\{|d_i|\}$, and equations (21) and (16) with some calculations we have:

$$\begin{aligned}\dot{V} \le\ & S_1(-\omega x_2 + k_1 x_{d1} - k_2(v_{sd} - v_{rd})) - (\omega|x_2| + k_1|x_{d1}| + k_2|v_{sd} - v_{rd}| + g_1 + d_m)\\ &+ S_2(-\omega x_1 + k_1 x_{d2} + k_2 v_{rq}) - (\omega|x_1| + k_1|x_{d2}| + k_2|v_{rq}| + g_2 + d_m)\\ &+ S_3(-\omega x_4 + k_3 x_{d3} + k_4 v_{sd}) - (\omega|x_4| + k_3|x_{d3}| + k_4|v_{sd}| + g_3 + d_m)S_3\\ &+ S_4(-\omega x_3 + k_3 x_{d4}) - (\omega|x_3| + k_3|x_{d4}| + g_4 + d_m)\end{aligned} \quad (19)$$

For any variable $z \in R$, $\pm z - |z| \le 0$ is straightforward. Considering this with some calculations, from (19), we have

$$\dot{V} \le 0 \quad (20)$$

According to lemma 1 the states of (14) with control law (15) is asymptotically stable. Thus the proof is complete.

The changes in system parameters, uncertainty and external disturbance can be expressed in the terms d_i, and with respect to (15)-(20) it is concluded that the system with the proposed controller is robust against uncertainties and rejects disturbances.

As mentioned d_m and g_i are control constants to compensate the errors of uncertainty and disturbances, which affect the system response and required control energy through uncertainty. Although any positive value $d_m, g_i \ge 0$ would be satisfactory according to (19) and (20), they should be selected in view of the design prospect to make a balance between system response and the consumed energy of control signals. $d_m = 0$, $g_i = 0$ would also be acceptable with no uncertainty and disturbances in the system.

1.1. Sliding Mode Controller design

Sliding mode controller design approach is composed of two main stages:

1. Design of a sliding surface (sliding manifold) so that the trajectories on this surface slides to the equilibrium automatically.
2. Obtain a control law to force the motion of trajectories onto the sliding manifolds [23-28].

Some papers have proposed controllers based on non-terminal sliding manifold (sliding surface). These surfaces are asymptotically stable which means are theoretically stable in infinite horizon. The finite-time stability of the sliding surfaces is the main part of sliding mode control design. Otherwise, with asymptotic stability of the sliding surfaces to the equilibrium, the controller will be useless and ineffective with practically large settling time (theoretically infinite). The necessary definitions [35], lemmas [34, 36] and stability proof [30] of the sliding surface of (21) are not included here for conciseness.

Consider the nonsingular terminal sliding surface in Proportional-Integral form of system error as below [30]:

$$s_i = c_i e_i + \int_0^t sign(e_i)|e_i|^{\alpha} d\tau, \quad i = 1,2,3,4 \quad (21)$$

where $c_i > 0, 0 < \alpha < 1$ are real constants.

The sliding manifold (21) is finite-time stable and the trajectories converge to the equilibrium point $e = 0$ in a finite time T_s satisfying the inequality of (22) [35-37].

$$T_s \le \frac{\left[V(e(0))\right]^{\frac{1-\alpha}{2}}}{\rho(1-\alpha)2^{\frac{\alpha-1}{2}}} \quad (22)$$

where $\rho = \min(\frac{1}{c_i})$

This could also be proved, with the Lyapunov function candidate of $V = \frac{1}{2}\sum e_i^2$ and the Lyapunov stability theorem and the finite-time modification of the theorem. A similar proof approach could be found in [35-37].

Proposed controller based on SMC

The error system (13) or (1) with the control law of (23) is asymptotically stable.

$$u_i = \frac{1}{b_i}\left(F_i + \frac{1}{c_i} sign(e_i)|e_i|^{\alpha_i} + l_i \frac{s_i}{c_i} + d_m sign(s_i)\right) \quad (23)$$

where $l_i, c_i > 0$ are real constants and $s_i, i = 1,2,3,4$ are the sliding surfaces.

Consider the following positive definite function as a candidate for the Lyapunov function.

$$V(t) = \frac{1}{2}\sum_{i=1}^{4} s_i^2 \quad (24)$$

Its derivative with respect to time is

$$\dot{V}(t) = \sum_{i=1}^{4} s_i \dot{s}_i = \sum_{i=1}^{4} s_i \left(c_i \dot{e}_i + sign(e_i)|e_i|^{\alpha} \right) \tag{25}$$

$$\dot{V}(t) = \sum_{i=1}^{4} s_i \left(c_i \left(F_i - b_i u_i - d_i sign(s_i) \right) + sign(e_i)|e_i|^{\alpha} \right) \tag{26}$$

Introducing the proposed controller from (23) into (26), we have:

$$\dot{V}(t) = \sum_{i=1}^{4} s_i c_i \{ F_i - b_i (\frac{1}{b_i} [F_i + \frac{1}{c_i} (sign(e_i) | e_i |^{\alpha} + l_i s_i + d_m sign(s_i))]) - d_i \} + s_i sign(e_i) |e_i|^{\alpha} \tag{27}$$

With some simple calculations, one has:

$$\dot{V}(t) = \sum_{i=1}^{4} - l_i s_i^{2} - d_m |s_i| - d_m s_i \le \sum_{i=1}^{4} - l_i s_i^{2} \le 0 \tag{28}$$

As mentioned in proof 1, considering $-|z| \pm z \le 0$, it is obvious that $\dot{V}(t) \le 0$ with the coefficients $l_i > 0$ so the system is stable in the sense of Lyapunov stability criterion and is robust against uncertainty and rejects external disturbances.

Remark 1. l_i are constants which have foremost effect on the controlled system response and used control energy. Its numerical value should be selected in view of the design prospect to make a balance between system response and the consumed energy of control signals. The schematic diagram of the proposed controllers is shown in Fig. 2.

Remark 2. Nonsingular terminal sliding manifold (21) is different from the previously reported terminal sliding mode (29) [38] and fast terminal sliding mode (30) [39].

$$s = \dot{e} + \beta e^{\frac{q}{p}} \tag{29}$$

$$s = \dot{e} + \alpha e + \beta e^{\frac{q}{p}} \tag{30}$$

where $\alpha, \beta > 0$, $p > q > 0$ are odd integers. Notice that for $e < 0$ we have $e^{\frac{q}{p}} \notin \Re$ so $\dot{e} \notin \Re$ that is in contrast with the system under study because only the real solution is considered feasible [35].

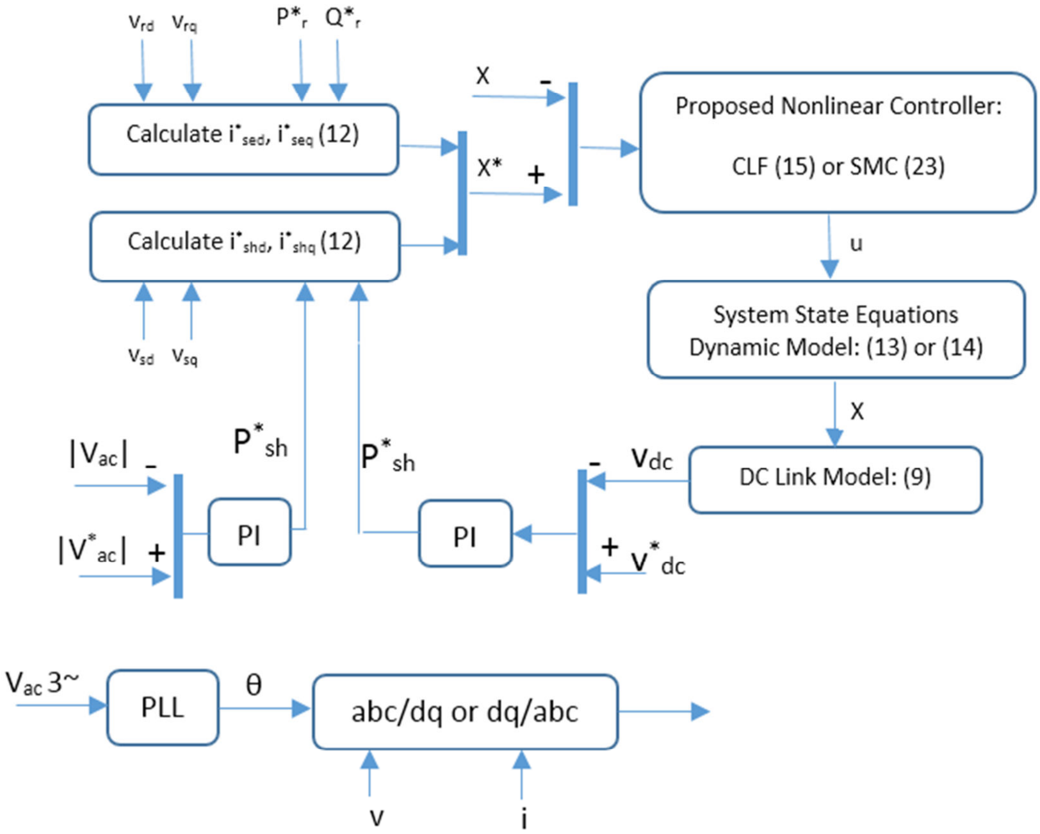

Fig. 2. Schematic diagram of the proposed nonlinear controllers

Remark 3. Undesirable chattering phenomena and discontinuity upon using the sign function in the control signals (15) and (23) can be removed by using a continuous function resembling the sign function instead [5]:

$$sign(z) \approx \tanh(\varepsilon \times z)\,,\, z \in R \qquad (31)$$

where, $\varepsilon > 0$ is a real constant. Consider that the error of above-mentioned sign function approximation could be compensated as the designed controllers are robust against uncertainties.

Remark 4. The proposed controller is different from the nonlinear controllers introduced in the papers.

Lyapunov Based Controller of [27] has proposed a direct feedback linearization technique, but it is based on the linearized system of the machine. Besides the paper does not include the UPFC which is investigated in this paper. It is obvious that the linear system under a nonlinear controller have yet the problems of linear methods; robustness and disturbance rejection.

The controller investigated in [2] is based on the Lyapunov method with Lyapunov function candidate of (32) satisfying the Lyapunov equation (33).

$$V = \frac{1}{2} e^T P e \qquad (32)$$

$$A_0{}^T P + P A_0 = -Q \qquad (33)$$

The matrix P is the result of (33), where Q is an arbitrary positive definite matrix, A_0=A-BK and K is the state feedback gain matrix. Solving the Lyapunov equation (33) and appropriate choose of the Q matrix is mathematically sophisticated. The row matrix K, is designed from Pole Placement technique [2], that is a linear control design approach rather than a nonlinear one. Pole Placement technique is not applicable if the system is nonlinear or not completely state controllable [40].

The design schedule in [18] has also investigated the state feedback technique with gain adjustment and nonlinear to linear system transformation. Calculation of the transformation matrices and the linear control theory approach are some drawbacks of the controller in [18].

The interaction between real and reactive power flow control is not completely omitted with the P-Q decoupled control scheme based on fuzzy neural network presented in [11].

Remark 5. The suggested nonlinear controllers (15) and (23) overcomes the problems mentioned in Remark 4 and are robust against uncertainties and parameter changes, reject external disturbances and also avoid the chattering phenomena.

3. SIMULATION RESULTS

It is considered that the parameters of the simulated system are corrupted by some uncertainties as well as the physical system [5]. Performances of the proposed controllers are evaluated using MATLAB/SIMULINK software. The simulation parameters of UPFC and the proposed controllers are presented in Tables 1 and 2, respectively.

Table 1. Parameters of the UPFC.

Parameters	R_{se}	$L_{se}\omega$	R_{sh}	$L_{sh}\omega$
Values	0.05(pu)	0.25(pu)	0.015(pu)	0.15(pu)
Parameters	$1/C\omega$	S_{base}	V_{base}	
Values	0.5(pu)	15.7 (KV)	1000(MVA)	

Table 2.Parameters of the proposed controller used in simulation.

Parameters	α	l_i	ε	c_i	g_i
Values	0.7	2.1×10^3	50	0.1	2.1×10^4

Five case studies are adopted similar to [2, 4, 5] changing the active and reactive power references through the transmission line. Finally, the angle between two buses is changed from -20 to -10 degree and after that, the reactive power referencethrough the line is set to zero (Q_{r_ref}=0). In all cases, the uncertainty factor is considered to be 10%. It means that the parameters of the system are increased to 110% of the values introduced to the controllers. Thus the controllers are unconscious of the exact value of the parameters. As the linear PI controller could not successfully control the system with parameter uncertainty and disturbances, the simulation for PI controller is done with no system parameter change (i.e. the parameters of the system are the same as the values introduced to the PI controllers).

Brief descriptions of the studied cases are presented in Table 3. With no UPFC there would be no control on the power flow through the line. So a constant power that's the function of the voltages of the buses (in magnitude and angle) flows through the line.

Table 3. Simulation description.

Simulation time (sec)	0	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
P_{ref}, (pu)	1.3	**2.3**	1.3	1.3	1.3	**2.3**	1.3	1.3	1.3	1.3
Q_{ref}, (pu)	-j0.5	-j0.5	-j0.5	**-j0.8**	-j0.5	**-j0.3**	-j0.5	-j0.5	-j0.5	**j0**
δ, (degree)	-20	-20	-20	-20	-20	-20	-20	-20	**-10**	**-10**
Parameter Uncertainty	**+10%** (Simulation parameters =110% of the value introduced to the controller except for PI)									

Simulation results show that the power flow through the transmission line and the DC link voltage are controlled effectively. The performance of the suggested CLF based controller is compared with proposed SMC and the PI controller with given parameters in Table 4.

The simulation results for active and reactive power flows are depicted in Fig. 3. System states results (i.e. $x=[i_{sed}, i_{seq}, i_{shd}, i_{shq}]^T$) and controller outputs (i.e. $u=[v_{sed}, v_{seq}, v_{shd}, v_{shq}]^T$) are illustrated in Fig. 4 and Fig. 5, respectively. It is obvious that the speed of the response and transient conditions are further improved in comparison with nonlinear and linear conventional controllers. The simulation results are scaled in Fig. 6 while both the active and reactive power references are changed simultaneously.

The 0.4 milliseconds transient time of the proposed CLF controller shown in Fig. 6 is sensibly significant compared to the results of linear [4] and nonlinear [2] methods and the proposed SMC and PI controllers. Fig 5 and 6 show that there is no chattering phenomena in the proposed controllers. Fig. 3 shows that the proposed controller has diminished the interaction between active and reactive power.

Table 4. Parameters of PI Controllers.

	Series Converter	Shunt Converter
K_P	0.27	0.3
K_I	61.3	65.6

Fig . 7 shows that the DC link and AC bus bar voltage. It can be seen that the pre-assumption of $V_{ac}=1pu$ is validated in simulation.

Equations (15) and (23) are composed of simple coefficients of system states and some constants. Obviously the system states used in the controller (currents) are locally measurable with inexpensive sensors. This is an important issue, because it avoids the measurement errors and data measurement delays. Besides, as the most simply measurable states of the system are used in the suggested controller, there is no need to design state space variable observer system [5].

Robustness against parameter changes and disturbance rejection properties of proposed CLF based controller and SMC are two important capabilities of the designed controller [41] which are the main weaknesses of the linear controllers. Robustness and disturbance rejection of the controllers cannot be ignored in practical applications, because of modeling errors, measurement errors, high order dynamics and nonlinear nature of power systems.

Figure (5) illustrates that the controller outputs are in a feasible and practical range of applications, leading to economic justification. The conventional UPFCs have the ability of following the proposed controller signals with no errors because the chattering phenomena and high order frequencies are avoided in the suggested controller.

As it can be seen the proposed controller has effective approach to control the system response through the uncertainty and disturbance conditions.

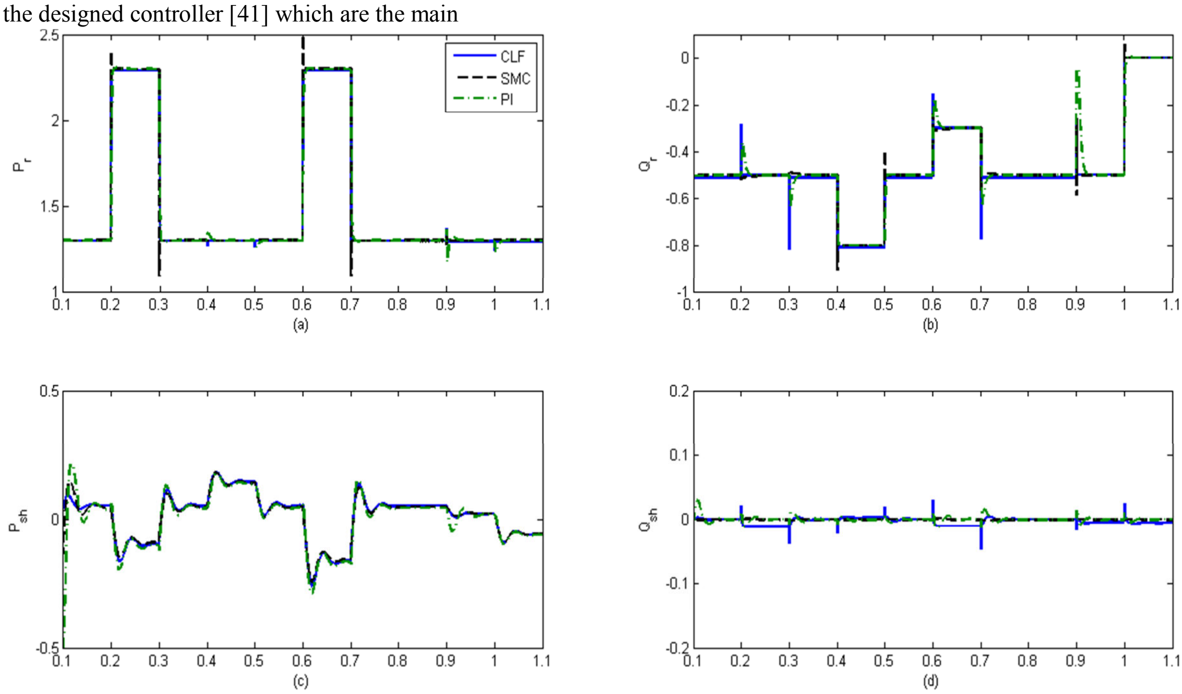

Fig. 3. Response of the UPFC system with 10% uncertainty according to the case studies. solid line: proposed CLF, dashed line: proposed SMC, dash-dot line: PI controller with no uncertainty.
(a) active power of the transmission line, (b) reactive power of transmission line,
(c) active power of the shunt converter, (d) reactive power of shunt converter.

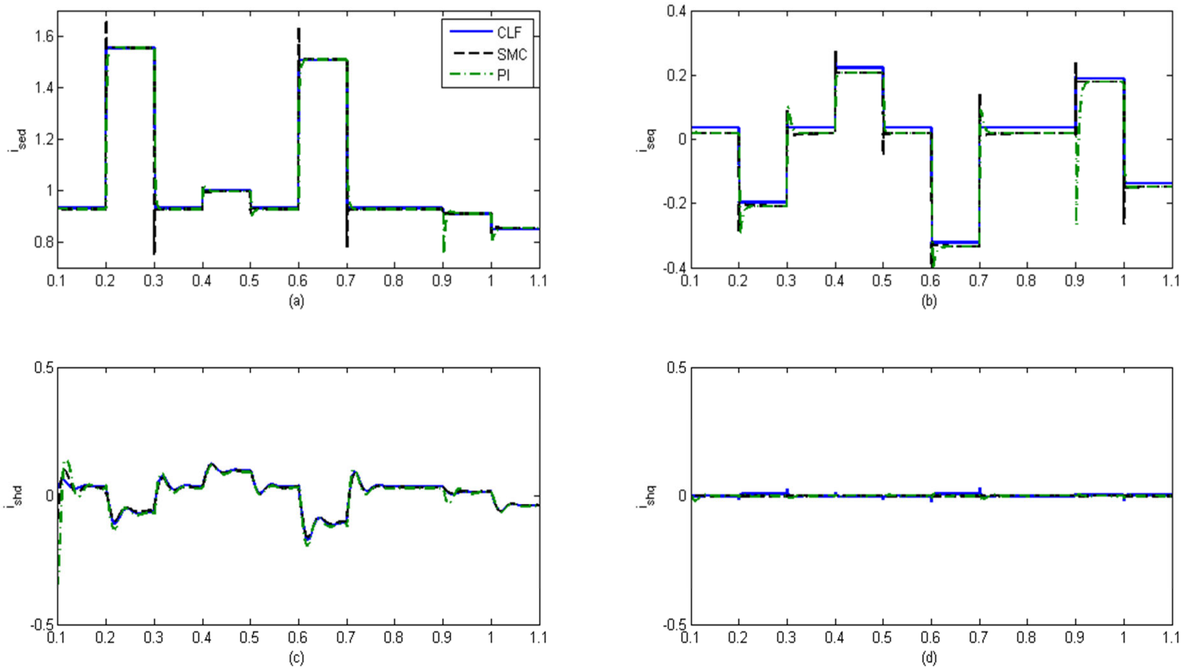

Fig. 4. Response of the UPFC system with 10% uncertainty. solid line: proposed CLF, dashed line: proposed SMC, dash-dot line: PI controller with no uncertainty.

(a) direct axis current of series converter, (b) quadrature axis current of seriesconverter

(c) direct axis current of shunt converter, (d) quadrature axis shunt of shunt converter

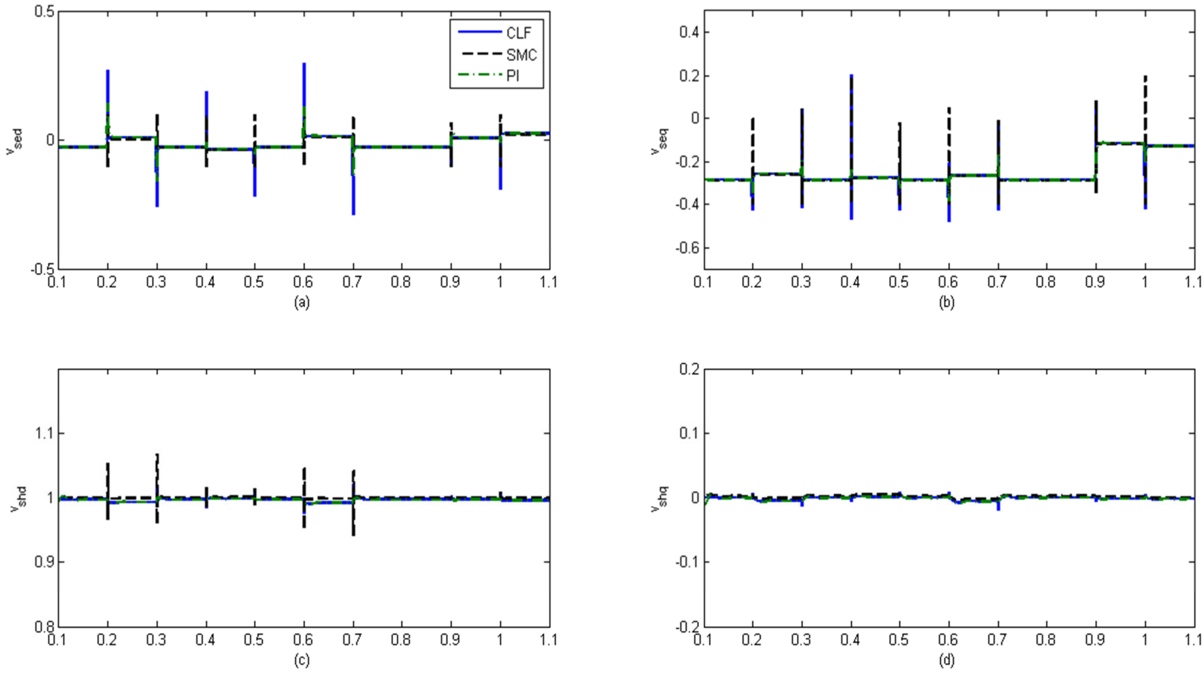

Fig. 5. Response of the UPFC system with 10% uncertainty. solid line: proposed CLF, dashed line: proposed SMC, dash-dot line: PI controller with no uncertainty.

(a) direct axis injectedvoltage of series converter, (b) quadrature axis injectedvoltage of seriesconverter

(c) direct axis injected voltage of shunt converter, (d) quadrature axis injected voltage of shunt converter

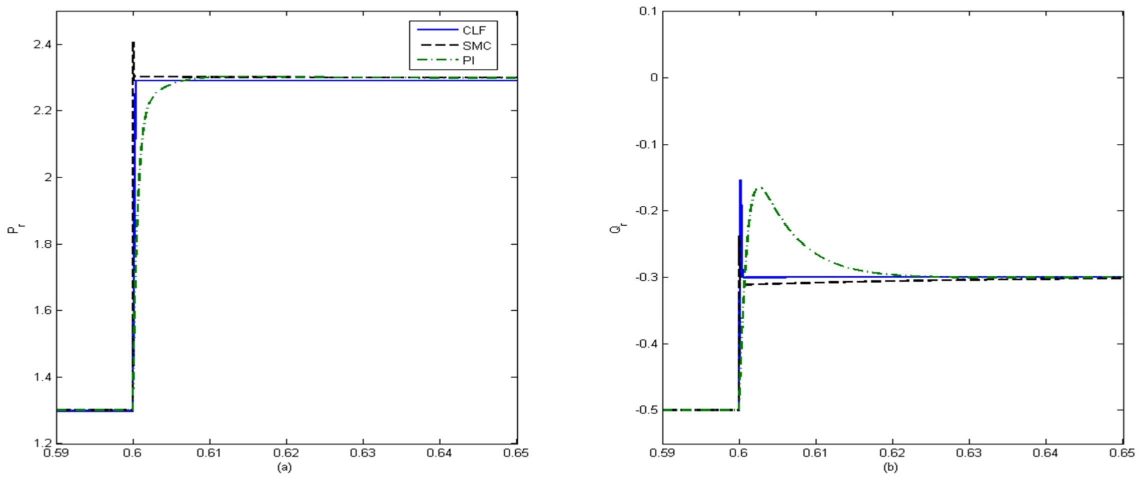

Fig. 6. Scaled response of the UPFC system with 10% uncertainty at t=0.6. solid line: proposed CLF, dashed line: proposed SMC, dash-dot line: PI controller with no uncertainty.

(a) active power through the transmission line; (b) reactive power through the transmission line

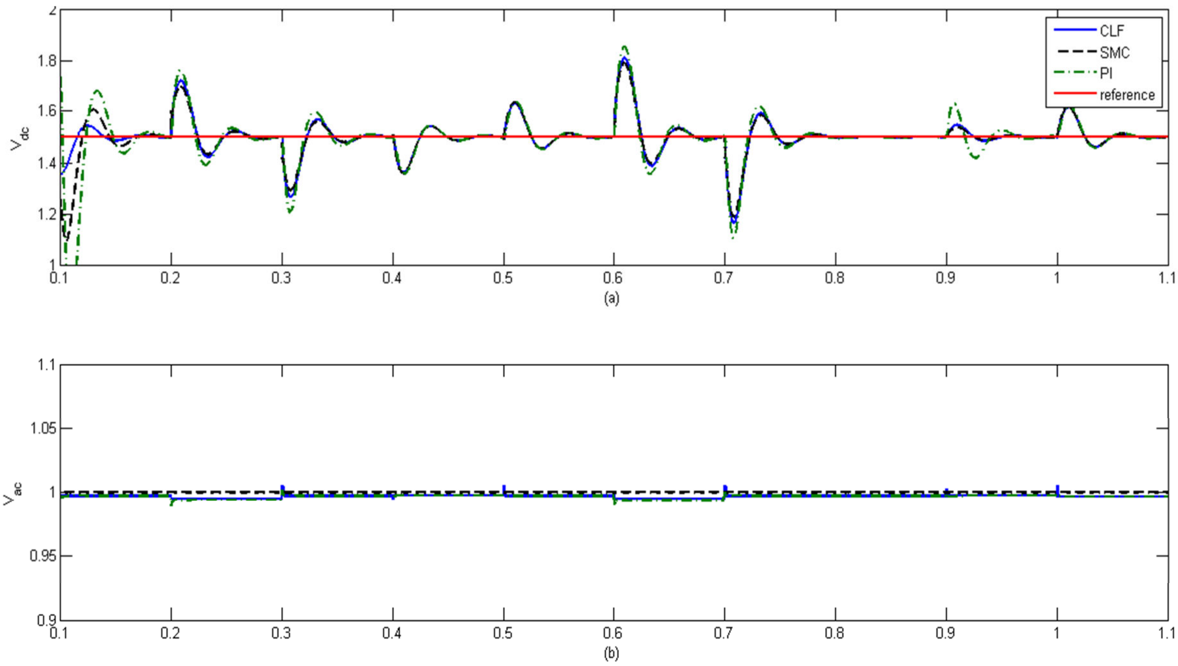

Fig. 7. (a) DC Link voltage, (b) AC bus voltage with 10% uncertainty. solid line: proposed CLF, dashed line: proposed SMC, dash-dot line: PI controller with no uncertainty.

4. CONLUSIONS

In this study, two novel robust nonlinear controllers are developed for power flow control of a power system using UPFC. One is based on the Control Lyapunov Function (CLF) and the other is based on the Sliding Mode Control (SMC). The designed CLF and SMC are able to stabilize the error trajectories of the system (i.e. converge to the origin $e = 0$) in a little settling time, reject disturbances and are robust against parameter changes and uncertainties. The stability of the proposed controller is mathematically proved by Lyapunov stability method. Discontinuity of controller is removed to avoid chattering and to achieve a continuous and smooth controller. The currents through the lines are used in the suggested controllers which are simply measurable and thus there is no essential need to the state space variable observer design. Numerical simulations confirm the theoretical results. Simulation results show the superiority of UPFC equipped with the proposed CLF and SMC over the conventional nonlinear and linear controllers in convergence time and robustness properties.

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